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Experimental testing of the performance of pipeline ploughs

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ABSTRACT

The influence of relative density and trenching depth on the pitch a pipeline plough travels at have been investigated by means of $1/50^{th}$ scale model plough testing. Tests were performed in dry sand at two relative densities with the model plough set up to form trenches of various depths. The relationships between plough pitch and depth are presented and compared between the two sand densities. The results show that relative density and depth can have a significant effect on plough pitch with possible repercussions for plough stability and trenching depth.

KEY WORDS: Plough; pitch; pipeline; trenching.

INTRODUCTION

Small diameter offshore pipelines are frequently buried in the seabed to a depth of several pipeline diameters. Burial is used as protection to prevent external loading from fishing activity/snags or hydrodynamic loading and to prevent movement of the pipeline during thermal expansion on commissioning (Finch et al, 2000).

One method of pipeline burial is ploughing. In this method, a pipeline plough is towed by a vessel to form a trench on the seabed into which the pipeline is placed. A second pass from a backfill plough is used to replace the soil from the spoil heaps above the pipeline to achieve an appropriate cover depth.

The two main areas of commercial operational interest with offshore ploughing are the achievement of an appropriate cover depth (with a flat trench profile) in a single pass of the pipeline plough, and the rate at which the pipeline ploughing can be carried out. Clearly, either the requirement for multi-pass ploughing or slow plough speeds will increase necessary vessel time and therefore cost.

Tow forces are believed to increase with both plough depth and velocity (e.g. Reese & Grinstead, 1986; Cathie & Wintgens, 2001; etc.). In particular, plough tow forces increase with rate at typical ploughing velocities allowing for only partial drainage of material being sheared (e.g. Hata, 1979; Reece and Grinsted, 1986; Os and van Leussen, 1987). Therefore, increasing relative density (which produces more dilation) and reducing permeability (which slows water flow to the dilating zone) also increase tow forces because of the amount of drainage that occurs during ploughing (Cathie & Wintgens, 2001). A pipeline plough vessel pulls with a certain maximum force, and so the maximum ploughing rate that can be achieved depends on the tow force – velocity relationship at the target trench depth for the soil encountered. Thus, accurate prediction of tow forces (both in terms of the forces for slow ploughing and the variation in tow force with velocity) allow for correct estimation of job duration and cost.

In addition, the stability of a pipeline plough during any trenching operation is critical to making steady progress with as few stoppages as possible. It is important for plough stability that the pitch (tilt along the length of the plough, see Palmer et al., 1979) is kept close to zero and constant to ensure the same trenching depth is maintained throughout the length of the trench.

This paper focuses on the effect that trenching depth and sand density have on the kinematics of a pipeline plough and is investigated experimentally by pulling a $1/50^{th}$ scale model plough at various trenching depths through loose (D_r = 26%) and dense (D_r = 76%) sand beds. The tests were all conducted in dry sand and therefore no investigation of rate effects was undertaken.

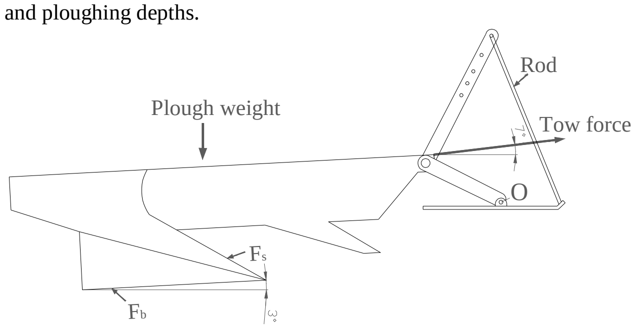
Plough kinematics

During operation, trenching depth is controlled by the skid settings and maintained by dynamic equilibrium of moments about the skids due to forces acting on the beam, share and its base. Figure 1 shows the main components of a plough and the force components that are acting on it for two different plough conditions.

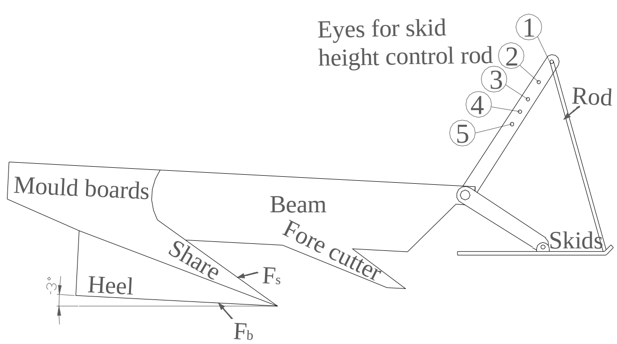
Figure 1a shows the plough trenching too deep which causes the share base to dig into the soil, thus increasing the upwards soil reaction force acting on it. The plough will regain moment equilibrium about the skid centre (‘O’ on Figure 1a) by clockwise rotation of the plough about the skid, which will reduce the trenching depth and the corresponding share base reaction force, F_b.

Figure 1b shows what happens if the plough tries to lift out of the soil (or rotate too far clockwise). The share base reaction force moves towards the tip reducing the lever arm between it and the centre of rotation at the skids. This magnitude of the share base reaction force also reduces due to reduced bearing area and so the force on the front of the share (F_s) and the self-weight force, W push the plough back to its correct trenching depth.

The above response is known as the long beam principle: depth control fails to work if the share is too close to the skids, thus necessitating a ‘long beam’. Further explanation on how a pipeline plough works was reported by Palmer (1979). These kinematics are examined in this paper by measuring the plough inclination for different soil conditions and ploughing depths.



(a): Plough trenching with a positive (aft) pitch



(b): Plough trenching with a negative (forward) pitch

Fig. 1: Schematic of plough configurations and forces

Recent research in the area of plough pitch and its effect on stability and trenching depth is limited and has been focussed on sea bed slopes such as sand waves (e.g. Allan, 2000; Morrow & Larkin, 2007). The pitch and depth of a plough can vary drastically as it crosses megaripples (sand waveforms of wavelength 0.6 – 30 m) and sandwaves. As the wavelength of megaripples can be very close to the length of a plough, and that of sandwaves is much greater, this causes large changes in plough pitch. This may cause additional loading on the rigid pipeline as there is insufficient adjustment on skid control and the roller box which supports the pipeline inside the plough (Morrow & Larkin, 2007). Hatherley et al. (2008) report a laboratory study investigating this behaviour.

Aims and objectives

The aim of the work described here is to show that sand density affects the pitch of a pipeline plough in a predictable manner which can then be accounted for by adjustment of plough settings to help ensure a smooth trenching operation. This should also help prevent any deviation in trench profile which may result and cause free spans to develop in the pipeline, inducing inherent stresses and making it more susceptible to hydrodynamic forces.

The work reported here will;

(1) Provide evidence that the 1/50th scale model plough acts in a similar manner to the real thing. Because there is limited research or field data on how plough pitch varies with depth and relative density, therefore tow force- depth behaviour was picked to compare between model scale and full scale.

(2) Provide data which clearly show the effect of sand density on plough inclination and explain behaviour whilst highlighting its importance with respect to real ploughing operation.

EXPERIMENTAL METHODS

Introduction

A series of 1/50th scale physical model ploughing tests were carried out to investigate the affect of trenching depth and soil relative density on plough performance. In particular, the effects of these parameters on tow force and the angle of the plough share were investigated. Tests were conducted at 1g. This gives the potential for increased dilation at model scale due to the very low effective stresses compared to prototype scale. This may make exact extrapolation of the small model effects to full scale difficult, but it is believed that the trends should remain the same.

The model plough

A 1/50th scale model plough was used in model tests. All dimensions of the plough were reduced by 50 and the mass by a factor of 50^3. The plough length was consequently 250 mm from the pivot point (‘O’) on the skids to the back on the share (Fig. 1a). This model plough was designed to work in the same manner as a full-scale plough and was tested by pulling through a sand bed as previously reported by Bransby et al. (2005) and Brown et al. (2006)

The model plough uses a manual skid height control system (shown in Fig. 1b) instead of a hydraulic system as used in full scale ploughs. Thus, steel rods were slotted into one of a series of eyes at one end and attached to the skids tips at the other to control the height of the skids. .

Testing apparatus

The apparatus used during the tests is depicted in Figure 2. The sand container was 2000 mm long, 500 mm deep and 500 mm wide out of the plane. Once a sand bed was placed in the container, the plough was placed on the soil surface on the left hand side of the box and pulled through the soil with a tow line. This towline was actuated with a winch powered by a DC motor through a pulley on the right hand side of the box as shown in Figure 2. The pulley was placed at a height of 100 mm above the sand layer to provide a realistic pulling inclination.

For tests where pitch was not measured, instrumentation consisted of a load cell of capacity 20 kg which was placed to measure the tow force and a draw wire transducer to measure displacement. The instrumentation of tests where pitch was measured consisted of a load cell and an inclinometer. No draw wire was used here because it was sprung and the small tensile force which the draw wire applied to the back of the plough although could easily be accounted for in terms of tow force may have altered the kinematics of the plough. Previous tests using a draw-wire transducer revealed that displacement rates were constant throughout each test and so the plough position at any time in a test could be ascertained by knowing the starting and finishing positions, the elapsed test time and the total testing time.

In tests, where the plough pitch was measured at different positions along the box the plough was displaced for a short distance (≈ 90 mm) before being stopped while the pitch was measured using an inclinometer. After each test, a steel ruler was used to measure manually the trench depth at points where pitch was measured using the inclinometer.

Plough pitch is defined here as the angle between the heel of the plough and the direction of displacement of the skids. Negative pitch is where the tip of the share defines the base of the trench (Fig. 1b) and positive pitch is where the back of the heel defines the base of the trench (Fig. 1a).

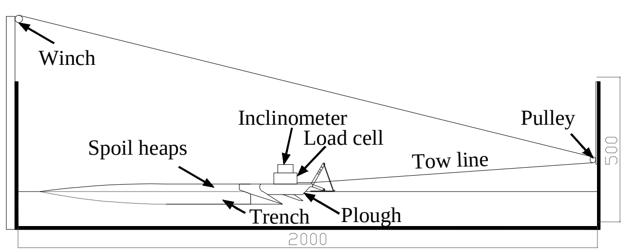


Fig. 2: Apparatus and test setup

Material properties

Poorly graded fine Congleton sand with D_{60} = 0.15 mm and D_{10} = 0.10 mm was used in all of the tests described here. Shear box tests revealed ϕ_{crit} = 31° and for D_r = 69%, ϕ_{max} = 40° over a normal effective stress range of 3 – 26 kPa. Standard laboratory tests gave G_s = 2.63, ρ_{max} = 19.48 kN/m^3 and ρ_{min} = 14.33 kN/m^3.

Sand preparation

For the tests in loose sand, the beds were prepared by first stirring to create a uniform density close to critical state. Following this, removal of the surface layers by scraping with a flat edge created a flat bed condition. The procedure resulted in a soil with unit weight, γ = 15.37 kN/m^3 corresponding to D_r = 26% (loose). Dense sand beds were prepared by pouring the sand from height through a slot pluviator which gave a relative density of 67% (γ = 17.36 kN/m^3).

RESULTS

Typical continuous trenching result

Figure 3 shows force-displacement data from a ploughing test set up to give a 23 mm deep trench in loose sand. No attempt was made to measure pitch and therefore the test was continuous from start to finish.

The instantaneous pick up of load must be due to friction as the plough is sitting on the surface of the soil at the start of the test. This is then followed by a gradual pick up of load as the plough penetrates into the sand and spoil heaps are formed. After a displacement of around 400 mm the plough then maintains its depth until the end of the test. This transition length is equivalent to 20 m prototype scale which is close to what is observed in the field where transition lengths of 25 – 50 m are most common and depend on soil conditions. The tow force when constant is known as the steady state tow force. The steady state tow force appears to drop off during this and some of the other tests due to the change in angle of the tow line as the plough gets closer to the pulley (see Fig. 2) as reported previously by Brown et al. (2006).

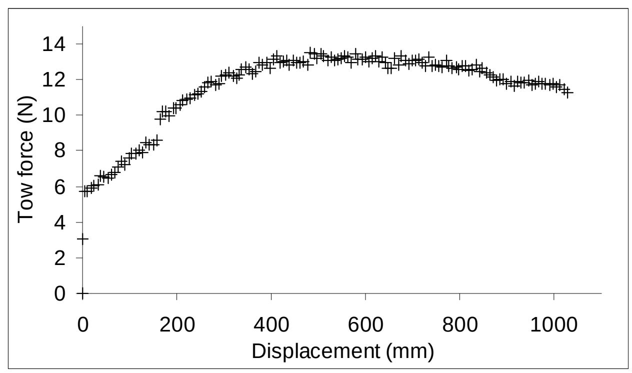


Fig. 3: Force displacement plot of typical plough test in loose sand.

Cathie and Wintgens (2001) developed an empirical model predicting tow force for different soil conditions, trench depths and velocities. This work brought together and adapted theoretical work by Reece and Grinsted (1986) with experience and data from a large number of ploughing operations. The tests reported here were conducted on dry sand and so would have provoked drained soil response in every test. There is therefore no rate-dependent velocity term as this is associated with partial pore fluid drainage. The tow force, F, will therefore be described by the remaining static components of the model:

$$F = C_w\, W + C_s\, \gamma\, D^3 \qquad (1)$$

Where C_w is a friction coefficient, W is the plough weight, C_s is a passive pressure coefficient which varies with density, γ is the unit weight of the soil and D is the trench depth.

Brown et al. (2006) suggested that C_w = 0.48 from the results of tests using the same model plough. Given a plough weight, W = 13.2 N, this can be used to predict a frictional-only tow force, C_w.W = 6.36 N. Note that this is very close to the initial tow force at zero displacement shown in Figure 3. Clearly, equation 1 can also be used to predict steady-state tow force and this is done in the next section.

Effect of trench depth on tow force

Ten plough tests were then conducted in loose sand, each with different skid settings designed to produce different trench depths. Figure 4 shows the steady state tow forces from the tests plotted against trench depth.

A comparison between the force/depth relationship for the 1/50th scale model in loose sand and the static component of the Cathie & Wintgens (2001) tow force prediction model is made in figure 4. The solid line in figure 4 shows the force prediction for dense sand and the dashed line the prediction for loose sand. The continuous line was generated using Eq. 1 with a C_s = 15 as recommended by Cathie & Wintgens (2001) for dense sand and the dashed line created using C_s = 5 as recommened for loose sand.

The comparison shown in figure 4 suggests that there is good agreement between the empirical model and the results using the dense sand parameters. This confirms the fact that the second term of Eq. 1 is proportional to D^3, but suggests that a higher value of C_s is required to fit the data, at least for the reduced scale tests conducted here.

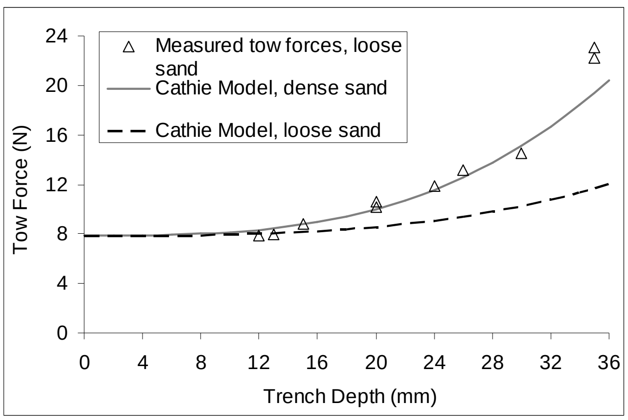


Fig. 4: Comparison of model plough results with Cathie and Wintgens (2001) force prediction model

Effect of soil density on tow force and pitch

Figure 5 shows results for two plough tests; one conduced in loose sand and the other in dense sand. The figure compares force, depth and pitch data for two complete tests from initiation of movement, through transition (0-350 mm for the loose test and 0-500 mm for the dense test) and into steady state.

The steady state trench depths are similar, with depths of 20 mm and 22 mm for the dense and loose sand conditions respectively. As expected the plough trenches slightly deeper in the loose soil. Even though the test in loose sand produces a slightly deeper trench and transition length tended to increase with depth for all tests, the loose test still required significantly less displacement to reach the steady state condition.. This may be due to the additional volume changes (and correspondingly larger spoil heaps formed) expected for the dense soil.

Despite the smaller trench depth observed during the dense sand test, the force required to pull the plough in the dense test is slightly higher than that for the loose test. The passive thrust developed in dense sand is likely to remain higher than that for loose sand as the plough moves forward continually forming new shear planes in dense virgin material with internal friction angle greater than ϕ_{crit}. The sand at the interface with the plough may always be heavily sheared and therefore a critical state angle of internal friction would be most representative for that shear plane. This may reduce the expected tow force in dense sand slightly.

Figure 5 also shows the variation of plough pitch during each test. Both ploughs start with negative pitch (tip down) as the share is only partially penetrating the soil at the start of the test but the skids rest on the surface. During transition, this pitch increases (the plough becomes more horizontal) as the share digs into the soil before the plough reaches a steady-state angle. The steady-state angle for the dense sand is almost exactly zero (i.e. there is horizontal inclination of the share base) but the steady-state pitch in the loose sand is +1.5^o (signifying that the back of the heel is lower than the tip).

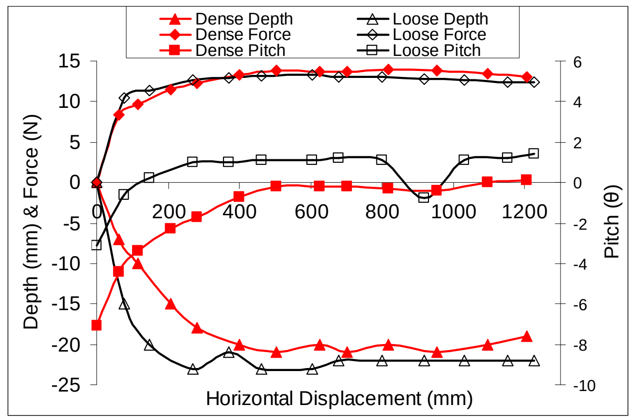


Fig. 5: Variation of depth, force and pitch throughout a test

Effect of soil density and trench depth on tow force and pitch

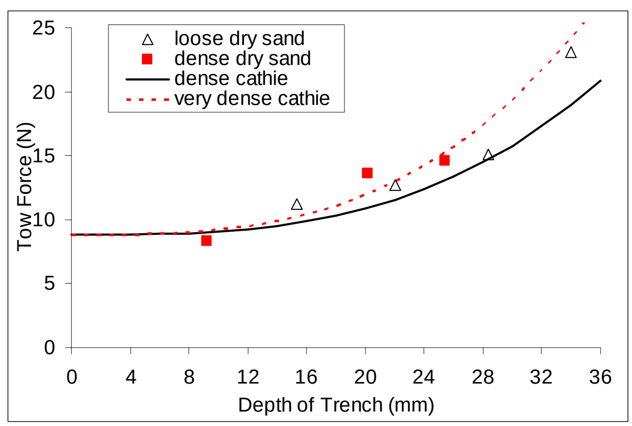


Fig. 6: Steady state force against depth comparisons for tests where pitch was measured.

Figure 6 plots steady-state tow forces against trench depth from a series of plough tests carried out in dense and loose sand. Some of these tests were carried out with a clinometer which allowed continuous measurement of pitch during each test.

The tow forces for the plough tests in loose sand in figure 6 are slightly greater than for the tow forces shown in figure 4 where pitch was not measured. This is likely to be due to the increased weight of the plough for tests where pitch was measured because of the addition of a 152g clinometer. Eq. 1 suggests that this would have increased directly the tow force by approximately 0.75 N due to the increased plough weight, W, but may have also affected the weight distribution.

Figure 6 shows that the measured tow force for the tests in dense sand was greater than for tests performed in loose sand. However, considering the large difference in relative density between the tests this difference is not as marked as one might expect.

The steady state pitch measured in the tests is plotted against trench depth in Figure 7. It reveals that the plough pitch decreased with increasing density and with trenching depth. There is a larger range of pitches for the loose sand tests partially because of the greater range of trenching depths but perhaps also because of the lower strength of the loose sand

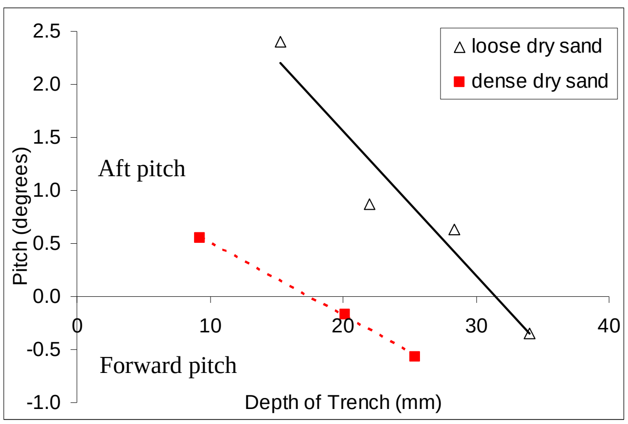


Fig.7: Effect of density and depth on plough pitch

DISCUSSION

Figure 4 shows a reasonable correlation between the scale model and prediction model for force depth behaviour. The 1/50th scale model tests conducted in loose sand do appear to match the Cathie & Wintgens (2001) model using parameters recommended for dense sand rather than for loose sand. A reason for this may be increased dilation at model scale due to reduced effective stresses as was stated by Bransby et al (2005).

The important point is that the magnitudes to the forces are similar and the tow force for the scale model appears to increase with the cube of the depth as is thought to be the case for the full scale plough (e.g. Reece & Grinstead, 1986). The two data points for a trench depth of 35 mm give higher measured tow forces than predicted by the Cathie and Wintgens (2001) model. However at this depth there is significant interaction between the beam of the scale model and the sand which would account for some tow force increase and a different force-trench depth relationship.

A possible explanation for such a small difference in tow force between the dense tests and loose tests in figure 6 is due to the difference in pitch between the tests. The geometry of the share is such that it starts as a point at its tip and increases in area towards its back. As a result there is less projected area cutting into the sand during forward pitching (i.e. in the dense tests here) compared with when the plough is aft pitching (in the loose tests).

The results shown in figure 7 may be explained by bearing capacity. The plough may pitch positively during the loose tests because the sand cannot support the plough without and pitch due to insufficient bearing capacity and by pitching backwards spreads its weight over a larger area, moves the heel reaction force (F_b) aft, and hence increases the lever arm of the heel reaction force about the skids. Due to the shape of the share of the plough (see Fig. 8), the trenching depth may influence the pitch of the plough because the greater the depth the larger the area of the share base available to support the plough weight This would also explain why shallower ploughing depths achieved greater pitches. Palmer (1979) states that pipeline ploughs tend to pitch backwards in soft clays and attributes this to insufficient bearing capacity.

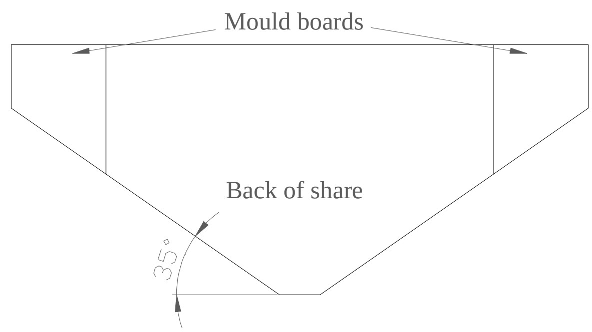


Fig. 8. Geometry of the back of a plough

Dense sand will have a higher bearing capacity and as a consequence the equilibrium pitch may be lower resulting in the share being less deeply buried than for loose sands. Dilation of dense sand as it is sheared at the interface with the heel and share base of the plough may also rotate the plough forward, further reducing the pitch. In addition, plough tests in dense sands require less change in pitch to increase share base reaction force (F_b) compared to tests in loose sand and may explain why there is a greater range of pitch in loose sand than for dense (Fig. 7).

Table 1: comparison between skid settings and trench depths achieved during 1/50th scale model testing

Skid settings: eye number	Set depth for no pitch (mm)	Depth in dense sand (mm)	Depth in loose sand (mm)
1	32	25	34
2	24	20	28
3	12	-	22
4	6	-	15
5	3	8	12

The effect of such small pitches in the plough can have substantial consequences. Table 1 shows the target trench depths based on skid settings and the depths achieved during the tests. For example, for a model plough set to trench at a depth of 32 mm for a 0º pitch condition, then a change of +1º pitch will produce a trenching depth of 36 mm. Conversely, the same plough running with a negative pitch of -1^{o} produces a trench defined by the depth of the tip of the share and thus a trench depth of 30 mm. If these changes occurred at full scale, these variations in depth with pitch are equivalent changes of trench depth of to +200 mm for the +1^{o} pitch and -100 mm for the -1^{o} pitch for a plough intending to trench at 1.8 m. Both cases are detrimental to an efficient trenching operation as trenching deeper than is necessary will increase tow forces and slow down progress, whereas trenching too shallow may require that a second pass is required to attain the specified cover depth.

CONCLUSIONS

A series of laboratory tests have been conducted to examine the trench depth-tow force relationships and kinematics of pipeline ploughs in sand. The tests revealed that:

- The results from the 1/50 scale model plough tests compared well with the Cathie & Wintgens (2001) model indicating that the scale model can be used to represent full scale ploughs

- Plough pitch may affect tow force due to share geometry.

- A plough trenching with only a moderate pitch of a degree or so (common in the field) is enough to change trenching depth by a considerable amount. This may lead to either not achieving the correct cover depth or trenching too deep therefore trenching inefficiently.

- Plough pitch reduces with trench depth and also with relative density of the ploughed sand

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